ENGINEERING MATERIALS

New Cryogenic Processing Approaches to the Development of High Strength-High Conductivity Wires for Magnet Applications

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The present project involves a new approach to the development of suitable wire products or pulsed magnet applications. The first portion of the project involves the development of a cryogenic drawing process where the dynamic recovery of copper can be inhibited. With this method, it may be possible to draw pure copper wire to a strength level of about 1 GPa with a conductivity of more than 85% IACS.

The first part of this project has already started, and some preliminary work was done. OFHC copper 101, supplied as 9.59 mm diameter rods, were drawn at both room and cryogenic temperature to 2.02 mm diameter wires. For the cold deformation, the wire drawing dies and the copper rod were, in the beginning, sub-immerged in liquid nitrogen until the complete thermal stabilization. Then, the dies were assembled in their cases, and the rods drawn as soon as possible. Dog-bone shaped tensile coupons were machined from the wires at 5 mm, 4.14 mm, 3.0 mm and 2.02 mm diameter, and then tensile testing was performed on an MTS machine at room temperature. At least two tests were done in each material condition.

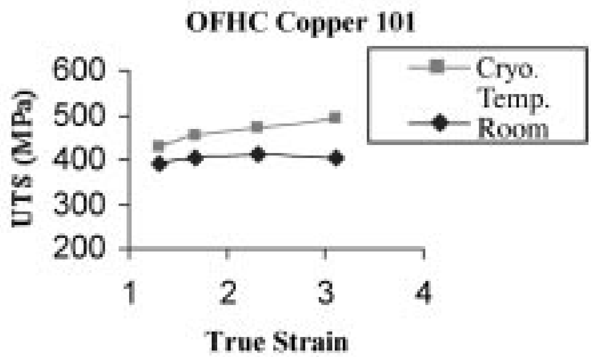

Figure 1. Ultimate tensile strength of Cu wires with several diameters drew at room and cryogenic temperature.

Figure 1 shows the changes in the ultimate tensile strength (UTS) with strain for the wires processed at both room and cryogenic temperature. Two distinguishing behaviors can be observed. The UTS of the wire drawn at room temperature changes from 392 MPa for $\varepsilon = 1.30$ (5 mm dia.) to 405 MPa for $\varepsilon = 3.11$ (2.02 mm dia.), which means that the UTS seemed to be independent of the strain in this range of deformation. This effect can be explained via dynamic recovery of the copper as processed at room temperature.[1] In contrast, the UTS of the cryogenic drawn copper increased from 430 MPa. ($\varepsilon = 1.30$) to 495 MPa ($\varepsilon = 3.11$), which shows that the processing at cryogenic temperature inhibited the dynamic recovery.

Reference:

1 Brandao, L., *et al.*, Processing and Fabrication of Advanced Materials VII, The Minerals, Metals & Materials Society, 347 (1998).

Tensile Strength and Electrical Resistivity of Cu-Nb/Ti Composite Wires

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The objective of this project is to develop and characterize conductor wires for high field pulse magnets. The materials were supplied as 9.9 mm diameter rods by Oxford, and were fabricated via wire drawing and/or swaging to a total true strain of 3.11. Fabrication involved a primary swaging of the rods to 7.7 mm diameter rods. They were then heat treated at 1043 K in argon for 24 hours, and were given a final processing to 2.03 mm diameter wires. This final processing was carried out by wire drawing (sample D), swaging (sample S) or swaging plus drawing (sample SD). For the basis of comparison, another rod was processed via drawing from 9.9 mm to 2.03 mm diameter wires, without intermediate heat treatment (sample DD). This report presents the mechanical and electrical property data of these Cu-Nb/Ti composite wires.

Table 1 presents the variation of properties (ultimate tensile strength (UTS) and IACS [%]), as a function of the fabrication method at 295 K and 77 K. Also presented is the calculated Taylor factor (M) for the four wires. In spite of the similarity in the values of M, the UTS of the wires fabricated by drawing was consistently higher than those that had swaging incorporated into their processing. This result was found to be in contradiction to the existing strengthening models (Hall-Petch type strengthening), which predict that the strength of these wires is proportional to M and the inter-fiber spacing. It is important to note that in this investigation, the inter-fiber spacing was also similar for all the wires. Further discussion on the strengthening model is presented in our second report, presented in this volume.

Quite noticeable in Table 1 is the fact that the wires drawn without swaging or heat treatment (DD) showed an exceptionally high strength—a UTS of about 1 GPa. This result is quite significant, because the UTS of 1 GPa is the threshold value required for conductor wires used in pulse magnet applications. The only drawback with the fabrication method used in this investigation is the apparent low IACS [%] values resulting from the processing. Efforts are now geared towards increasing the IACS [%] value to a more respectable value through restacking/rebundling processing techniques.

Table 1. Ultimate tensile strength, IACS and Taylor factor "M" of the Cu-Nb/Ti wires.

Sample ID	295K		77K		Taylor Factor (M)
	Average UTS (MPa)	IACS[%]	Average UTS (MPa)	IACS[%]	
S	556	48.41	830	246.95	3.26
SD	660	48.33	908.5	229.79	3.13
D	749	48.90	951	230.44	3.15
DD	838	55.22	1080.73	343.80	3.14

The Influence of Heat Treatment on the Properties of Heavy Deformed Cu-Nb/Ti Composite Wires

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Reasonable values of strength and electrical conductivity have been attained in a variety of heavily deformed materials, e.g. Cu-Ag and Cu-Nb composites.[1-3] Such heavy deformation can be accomplished through wire drawing or swaging. Additional improvements in the properties of Cu-Ag systems have been reported.[1] This was achieved by employing intermediate heat treatment, which promoted the precipitation of Cu and Ag in the solid solution. In this investigation, attempts were made to (a) establish if there is any effect of intermediate heat treatment on the properties of processed Cu-Nb/Ti wires, and (b) reconcile the strength of the processed wires with existing strengthening models, especially those based on Hall-Petch-type strengthening.

Two batches of Cu-Nb/Ti wires were fabricated and evaluated. The first batch was produced by drawing or swaging, combined with an intermediate heat treatment, while the second batch was without heat treatment. Figures 1(a) and 1(b) present a Hall-Petch-type plot of the average microhardness (Hv) versus inverse square root of the inter-fiber spacing (λ) for the drawn and swaged wires, respectively. In both cases, the hardness of the non-heat treated (NHT) wires were higher than the heat-treated wires (HT) at low processing strain. At high processing strain, however, the hardness values of the wires approached a constant value, and did not depend on the inter-fiber spacing (λ). This suggests that the Hall-Petch-type strengthening model is inadequate in its current form to predict the strength of this material at high processing strain. Furthermore, one can also infer that there exists a hardness limit (threshold value) for different processing methods. Based on the Barrier model (Hall-Petch-type strengthening model), strength or hardness can remain constant with decrease in λ, only if there is a simultaneous reduction in the density of dislocation. Such a process can occur, in the light of the occurrence of dynamic recovery or recrystallization in this material.

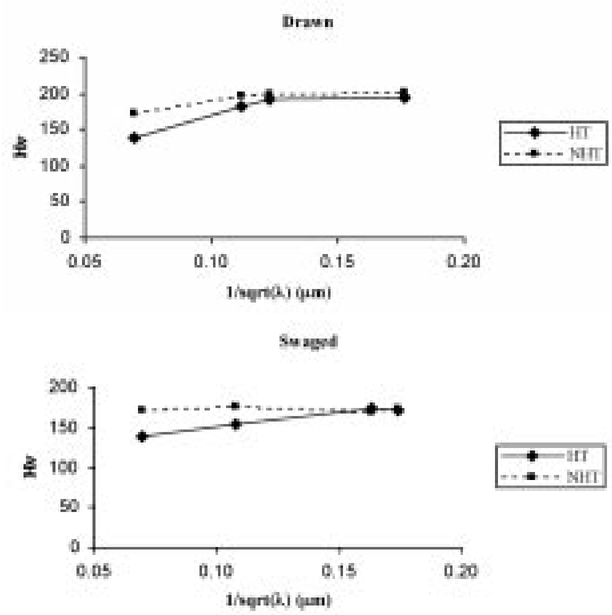

Figure 1. Microhardness vs. inverse of the square root of the interparticle spacing.

References:

1 Sakai, Y., *et al.*, Acta Metall. Mater., 43, 1517 (1995).
2 Dupouy, F., *et al.*, Scripta Materialia, 34, 1067 (1996).
3 Raabe, D., *et al.*, Z. Metallkd., 86, 405 (1995).

Magnetic Field Processing of Polymers

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We have been investigating the orientation of liquid crystalline thermosets in high magnetic fields. The goal of this work is to demonstrate the feasibility of using magnetic fields to provide macroscopic orientation and improved mechanical properties for structural applications. The specific system we have investigated is a liquid crystalline epoxy, 4,4'-diglycidyloxy-α-methylstilbene, with the hardener sulfanilamide. These materials are cured in a magnetic field and the orientation subsequently measured by wide-angle x-ray scattering (WAXS). High orientation parameter values of 0.75, on a scale of 0 to 1, can be obtained even at low field strengths of 3 T. Measurements of orientation as a function of magnetic field strength for two levels of B-staging (pre-curing) show significant differences in the threshold field strength required to obtain orientation. The measurements were conducted on samples with no B-staging and samples with 2 hours B-staging time. The higher threshold field for B-staged materials is due to the increased viscosity caused by the B-staging. Results also indicate, however, that at high magnetic field strengths orientations are higher for the B-staged materials than for the non-B-staged material.

In order to obtain more detailed information on the role of the process variables in controlling the orientation, we have created a fractional factorial design to study the main and combined effects of the magnetic field strength, processing time in the field, and amount of B-staging. Analysis of the results of the orientation parameter data for different combinations of these process variables yielded a model which describes the effects of the three input variables on the orientation parameter. The coefficient of determination for the model is 0.8577. An optimization of the model revealed a very good predictability of the input variables given the desired orientation parameter. Four samples were prepared, and the predicted orientation parameters compared to the experimentally determined values. For three of the samples the results are well within the 95% confidence limits of ± 0.24 given for the model. The fourth sample has a predicted orientation parameter of 1.48, well above the theoretical limit of 1, and the experimentally determined value is 0.57, well outside the 95% confidence limits. The model cannot account for the theoretical upper limit of the orientation parameter without severely distorting the model. The results for the three other samples, however, indicate that the model can predict the orientation parameter for a given set of processing conditions when the model predicts physically realistic values.

Mechanical and Thermal Properties of Unreinforced Polyphenylene at Cryogenic Temperatures

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Summary. A collaborative effort between NHMFL and Maxdem Incorporated to evaluate the potential of high strength polymers for magnet and cryogenic applications has been completed. Tests on two high strength polymers fabricated by Maxdem were conducted at NHMFL to generate mechanical and thermal property data at 295 K, 77 K, and 4 K. The polyphenylene materials (PARMAX-1000 and PARMAX-1200) are unreinforced thermoplastics that can be compression molded into desired shapes. Testing was divided into four distinct areas: tensile tests to obtain the modulus and tensile strength of the materials, compression tests to obtain the compressive strength, flexural tests to obtain flexural strength, and thermal contraction measurements at 77 K and 4 K.

Results. The properties of the two plastics are very similar. The fracture strengths are around 350 MPa at 295 K. The elastic modulus of the 1200 material is roughly 8 GPa at room temperature, and increases to 10 GPa at liquid helium. The 1000 series material is slightly stiffer with a 295 K modulus of 10 GPa increasing to 12 GPa at 4 K. These numbers represent strengths that are approximately five times greater than typical thermoplastics, while the modulus is a factor of 2 higher. A similar high performance plastic called PEEK (poly-ether-ether-ketone) has a 4 K strength and modulus of 190 MPa and 7 GPa, respectively.

The thermal contraction upon cooldown from 295 K to liquid helium of the 1200 and 1000 materials are 0.56 % and 0.47 %, respectively. These values are roughly half when compared to commercially available composites such as NEMA G-10. The thermal contraction of G-10 at 4 K is about 0.71 % in the normal laminate direction, and around 0.25 % for directions parallel to the fiber reinforcement.

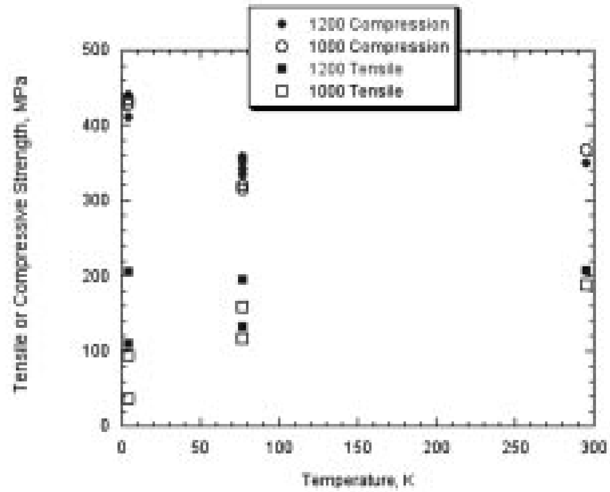

Figure 1. Strength vs. temperature for Parmax 1000 and 1200.